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## **Integrated Surface Emitting Laser Arrays with Flat-Tip Microprobes for the Near-Field Optical Data Storage**

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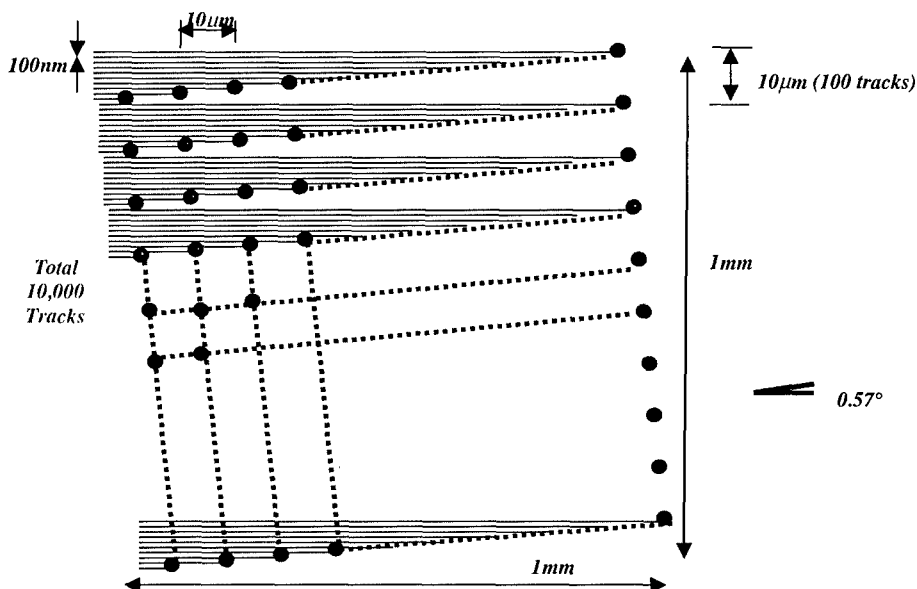
### **ABSTRACT**

Current optical data storage is challenging to increase its memory capacity and data transfer rate for realizing high-quality image and rapid service in the coming digital, multimedia and network era. To actualize more effective and simple data storage, a novel parallel near-field optical system has been proposed using vertical cavity surface emitting laser (VCSEL) microprobe arrays. The new parallel optical system is based a multibeam recording head consisting of a VCSEL array with apertures of nanometer size as a near-field wave exit. We have developed some candidates for the parallel recording head, including the direct aperture formation on the VCSEL emitting surface and the preparation of microprobe arrays with flat-tip structure. The new flat-tip microprobe array has advantages for improving the optical efficiency and stabilizing the contact head system with optical media since it is prepared from semiconductor materials of high refractive index. Silicon nano-aperture probe array has been prepared successfully with the aperture size of 150 to 500nm using micro-fabrication techniques. We have also investigated the integrated microprobe array by the direct fabrication of flat-tip probes on the substrate of bottom emitting VCSEL arrays. Finally the reading mechanism has been studied theoretically using a finite difference time domain (FDTD) simulation and an optical feedback effect of semiconductor lasers for the integrated microprobe VCSEL array. We believe this nano-aperture VCSEL probe array is sufficiently effective to be applied to the parallel recording head for the near-field optical data storage of a high data capacity and fast transfer rate.

### **INTRODUCTION**

Both a high data capacity and fast transfer rate are required in the fields of magnetic and optical data storage. In the last ten years, several near-field optical data storages have been developed to increase a data capacity using evanescent waves. However, these still have a limitation to speed up a data transfer rate to follow the ability of magnetic hard disk system. In order to overcome this speed barrier of optical data technology, some approaches such as 2-D parallel near-field recording and 3-D holographic system have been proposed and studied [1]. Since two dimensional array system which was proposed by our research group is based on a multibeam recording with the small spot size using the microprobe and VCSEL array, it has advantages for realizing both a fast data transfer rate and high memory capacity [2,3]. As shown in figure 1, the VCSEL array will be inclined at a specific angle (for example,  $0.57^\circ$  for  $100 \times 100$  array head) to the track direction to align all light sources on separate data tracks. In this array head, all lasers will be manipulated simultaneously to record the data on and read them from

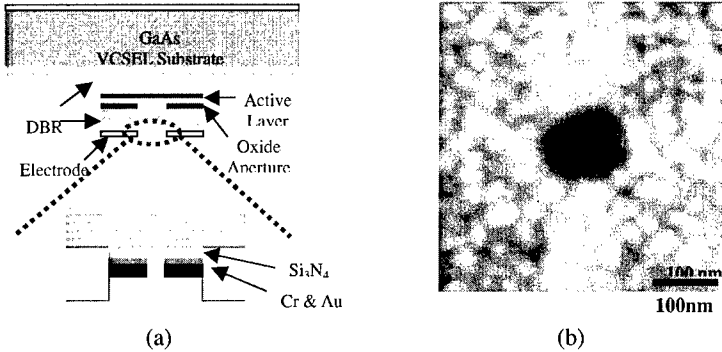
multi- tracks, resulting in a huge increase of the data transfer rate. The realization of small laser beam with sufficient power is another requirement for increasing the memory capacity in this parallel optical system. Thus, the fabrication of nano-aperture microprobes having high optical efficiency will be a key process to expose a strong near-field wave on the optical media. In order to realize this two-dimensional optical data storage, we have developed some array head systems, including the direct aperture formation on the VCSEL emitting surface and the preparation of microprobe arrays with the flat-tip structure. New microprobes of flat-tip structure are prepared from semiconductor materials having high refractive index so they have advantages for improving the optical efficiency and stabilizing the contact head system with the optical media. The concept and fabrication process for new array heads are discussed with their optical properties and microstructures in this paper. In order to apply theses new types of array heads to the actual near-field optical head, we have also been developing the integrated microprobe array by preparing flat-tip microprobes directly on the substrate of bottom emitting VCSEL arrays. The structural design of the integrated VCSEL microprobe array will be discussed with simulation results for the reading mechanism from the phase change media using a finite difference time domain (FDTD) analysis and an optical feedback effect on the semiconductor laser.



**Figure 1.** Schematic diagram of the two-dimensional array system to realize a high data transfer rate. VCSEL array is inclined at a specific angle (for example, 0.57° for 100x100 array head) to the track direction to align all light sources on separate data tracks.

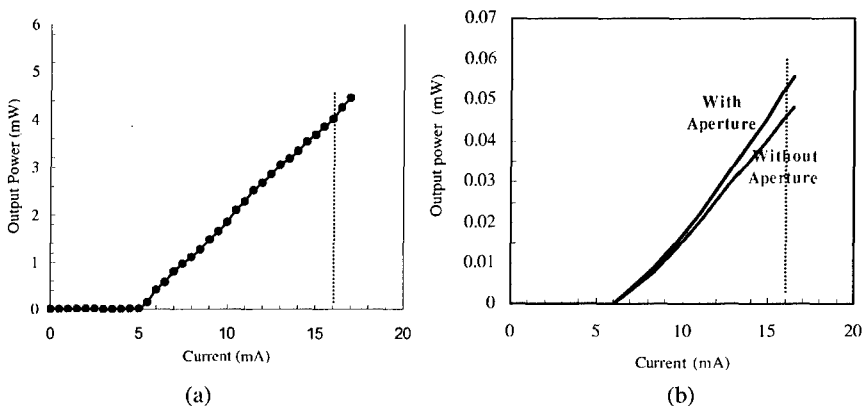
# NANO-APERTURE VCSEL ARRAY

Since our parallel recording system must include a VCSEL array as light sources, it is a good idea to use a VCSEL array for the exit of near-field waves without any other components. Thus, we have studied the fabrication of simple head structure using a nano-aperture VCSEL array, where a tiny aperture is formed directly on the emitting surface of VCSEL using the focus ion beam (FIB) method as shown in figure 2(a). In order to realize the best optical efficiency, a phase matching layer of  $\text{Si}_3\text{N}_4$  film was first deposited on the VCSEL surface with a specific thickness of 107.3 nm, and the metal deposition of thin Cr adhesion layer (5 nm) and Au reflective layer (50-200 nm) was followed. Then, a small nano-aperture was formed on the VCSEL emitting surface through metal layers using the FIB equipment. We could control the FIB etching conditions and thus, fabricate very small apertures of around 50 nm size successfully. AFM image of the VCSEL emitting surface after the aperture formation is shown in figure 2(b). An aperture of around 100-nm-diameter is formed on the surface through metal layers where the metal surface also shows a good property with the surface roughness below 10 nm (p-v).



**Figure 2.** (a) The preparation procedure for the nano-aperture VCSEL array with a dielectric layer of  $\text{Si}_3\text{N}_4$  and metal reflective layers of Cr and Au. (b) AFM image of the 100-nm-diameter aperture prepared on the emitting surface of VCSEL.

The optical output of nano-aperture VCSEL was measured with a photodetector in the far-field range using a collecting lens before and after the aperture formation, and the result is summarized in figure 3. The VCSEL used in this measurement has the optical output of 4.1mW at the 16mA current before the deposition of dielectric and metal layers (see figure 3(a)). With the deposition of dielectric and 50-nm-thick metal layers, the output power of VCSEL drops to 0.054mW at the same current as shown in figure 3(b). This small power comes from the leakage light through the reflective metal layer since it is not sufficiently thick to block the laser light entirely. If we increase the thickness of the metal reflective layer, the leakage light will disappear, however, it is also difficult to penetrate the near-field light through a long hole after the nano-aperture formation. Thus, we have fixed the thickness of the reflective metal layer as 50 nm in this research.



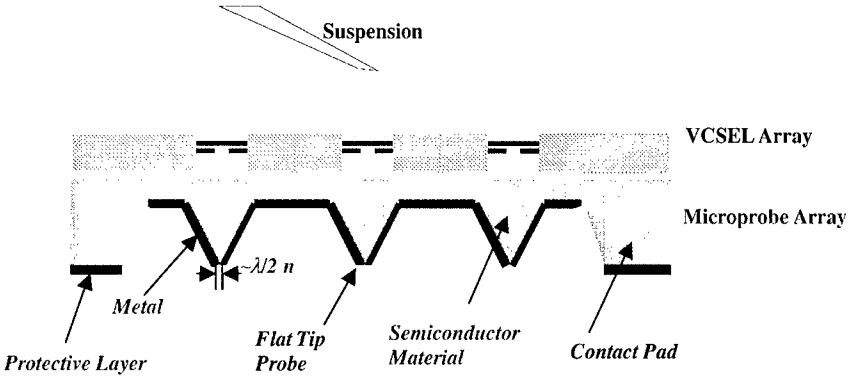
**Figure 3.** I-V characteristics of VCSEL; (a) before the metal deposition and (b) after the metal deposition and the aperture formation. A tiny aperture of 100-nm-diameter was formed on the VCSEL emitting surface, which results in a little increment of the output with around 7  $\mu$ W.

The VCSEL output power shows a little increment of around 7  $\mu$ W after the formation of 100-nm-size aperture (see figure 4(b)). Even though we need more data for the beam size and power distribution in the near-field range, this result indicates the possibility to apply the nano-aperture VCSEL head to the recording application. However, this output increment is not sufficient for the actual optical recording system since the optical media usually requires more power to be recorded. Therefore it is strongly required to increase the optical output while keeping the small aperture size for the light exit. There are some possible approaches to increase the optical power with a tiny aperture, including the surface plasmon enhancement [4] and the introduction of microprobe arrays. Thus, we have developed new type of flat-tip microprobe arrays to realize higher optical throughput and better structure design for the contact head required in our parallel optical system [5]. This flat-tip microprobe array will be combined with a VCSEL array to realize the parallel near-field recording head.

## FLAT-TIP MICROPROBE ARRAY

The optical power and efficiency of new flat-tip probe arrays strongly depend on the shape and aperture size of microprobes. Since the fundamental propagation wave in metal-coated microprobes decays rapidly below the cutoff diameter that is defined theoretically as  $\lambda/2n$ , it is possible to obtain small spot size without a huge power loss if semiconductor materials having high refractive index are used for the microprobe array. Thus, we have developed better recording array structure using the flat-tip microprobe, as shown in figure 4. This microprobe structure has another advantage in its uniformity of probe height, which is very important for our contact head system. Since contact pads are in touch with the disk via a very thin lubricant layer, the recording gap can be controlled by the small height difference between the contact pads and

probe tips. In our probes, both surfaces of the flat-tips and contact pads have the same height after the etching process because both are prepared from the same wafer plane. After depositing a very thin protective layer of 10 nm thickness only on the contact pads, we can keep the distance between the probe tips and disk surface at around 10 nm.

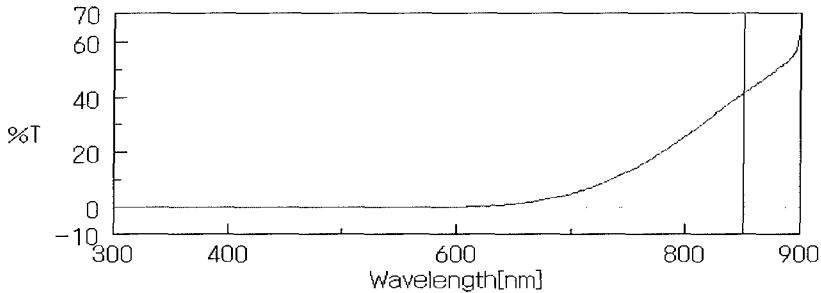


**Figure 4.** Schematic diagram of the parallel near-field optical memory including a VCSEL array and flat-tip microprobe array. The gap between the flat-tip surface and media surface is controlled by the thickness of the protective layer deposited only on the contact pads.

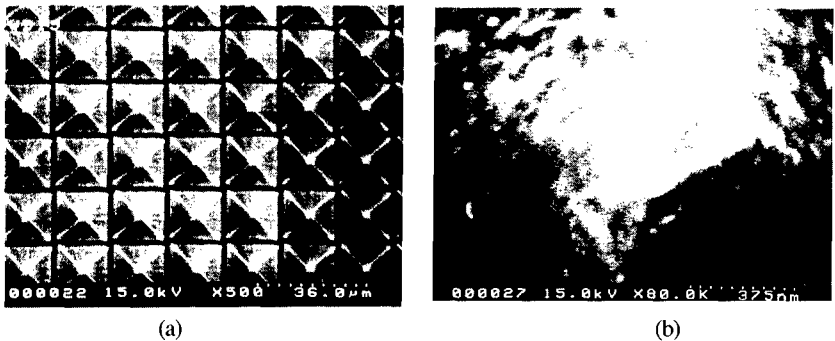
Semiconductor single crystals are the best candidate material for the flat-tip microprobe array since they have a high refractive index and are manipulated easily with a stable micro-fabrication process. We have selected three different wafers for the flat-tip probe array, gallium phosphide for the 650 nm, silicon for 850 nm and gallium arsenide for 980 nm wavelength applications. They have a high refractive index and negligible extinction coefficient at their specific wavelengths except silicon. Silicon has an extinction coefficient of 0.004 at an 850 nm wavelength so it may not be suitable for the optical application. However, if we use very thin silicon wafer, the light can penetrate through it at that wavelength. For example, a laser beam of 850 nm wavelength can penetrate with 43.7% transmittance theoretically through the 14- $\mu$ m-thick silicon wafer, as calculated using Lambert's law defined as  $T=I/I_0=\exp(-4\pi kt/\lambda)$  [7]. Figure 5 shows the experimental data of transmittance for the thin silicon substrate of 14  $\mu$ m thickness. With an anti-reflection (AR) coating of  $\text{Si}_3\text{N}_4$  layer, the thin Si substrate results in the transmittance of 40% at 850 nm that shows a good agreement with the theoretical calculation. Although we lose around half of optical power with the 14- $\mu$ m-thick wafer, silicon is still attractive for the microprobe array due to its high refractive index and well-developed microfabrication process.

We used the microfabrication technique to prepare flat-tip microprobe arrays with nanometer size apertures using the silicon-on-insulator (SOI) wafer, consisting of the 14- $\mu$ m-thick silicon layer, 0.5- $\mu$ m-thick silicon oxide layer and 400- $\mu$ m-thick silicon substrate. Figure 6 shows SEM photomicrographs for the flat-tip microprobe array and the nano-aperture prepared on the microprobe tip. The array consists of 625 microprobes and three contact pads even though SEM photomicrograph includes only some part of microprobes, where each microprobe has 17  $\mu$ m edge and 12  $\mu$ m height with the 20  $\mu$ m pitch (see figure 6(a)). The microprobe has a 70 deg

angle between two side planes; however, it shows the flat area on the probe tip as a result of careful control for the silicon etching process. Top surface of microprobes has a square shape with the edge length of 150 to 500 nm even though some probes of rectangular surface are included in the array. Though they have a little variation in size, all microprobes in the array have the same height because top plane was prepared from the same surface of Si wafer. The smooth surface of microprobes also enables the optical wave to propagate into the microprobe without any scattering loss and, thus, it will be another important advantage of the flat-tip microprobe. In order to apply the microprobe array to an actual recording head, the outside of microprobe must be coated with the reflective metal layer and followed by the formation of tiny aperture on the probe tip for the exit of laser beam. In this research, we have developed new mask process for making an aperture on the flat-tip microprobe that is suitable for the array system and mass production. In this method, the  $\text{SiO}_2$  mask layer on the tip (it is used originally for the probe fabrication) was re-sized from  $12\text{ }\mu\text{m}$  to  $1.3\text{ }\mu\text{m}$  with the careful control of isotropic etching rate. After depositing metal layers from both the top and side directions, we etched out the remaining  $\text{SiO}_2$  mask, resulting in the tiny aperture on the microprobe tip, as shown in figure 6(b). More detailed process and microstructural evaluation for this flat-tip microprobe array has been discussed in the previous paper [5].



**Figure 5.** Experimental data for the optical transmittance of the  $14\text{-}\mu\text{m}$ -thick silicon having an anti-reflection (AR) coating. It shows around 40% transmittance at an 850 nm wavelength.

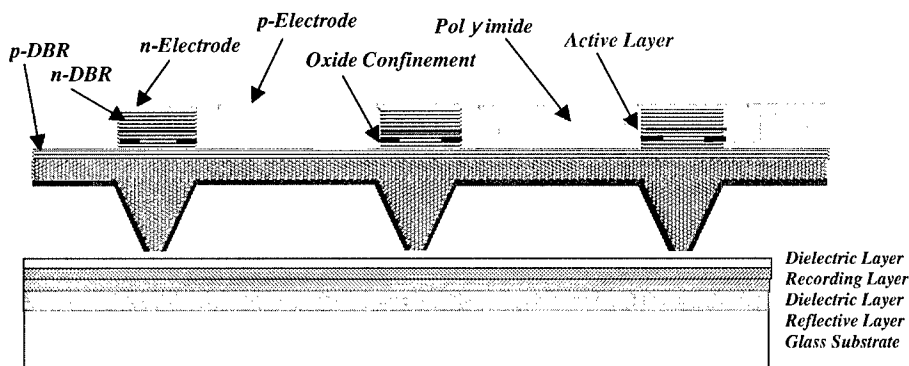


**Figure 6.** SEM photomicrographs of (a) the flat-tip microprobe array and (b) the nano-aperture prepared on the probe tip. The microprobe array consists of 625 probes and three contact pads.

## INTEGRATED VCSEL MICROPROBE ARRAY AND READING SIMULATION

### Integrated VCSEL microprobe array

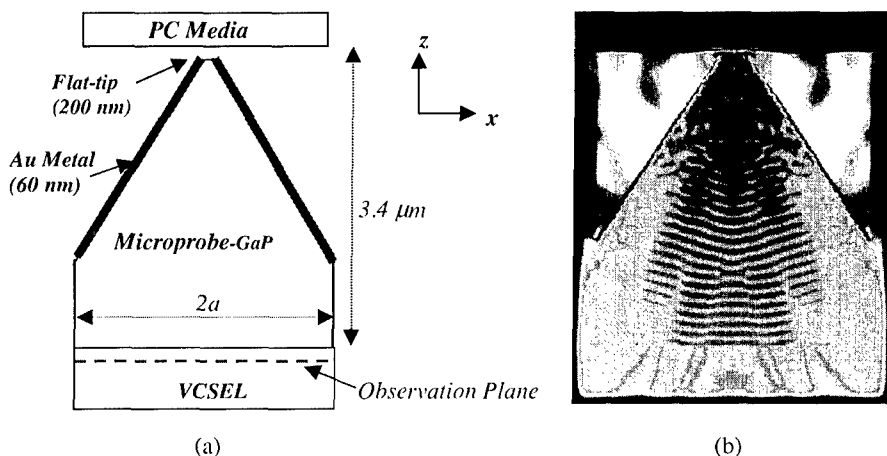
Although we have proposed new concept of flat-tip microprobes for the high optical throughput and realized the microprobe array with silicon and GaP [5,6], it still requires further improvement to complete the near-field optical system, including the alignment and bonding of the microprobe array to VCSEL array. Thus, we have studied the integrated VCSEL array head using a bottom emitting VCSEL array. As shown in figure 7, the light travels downwards through the substrate in this type of VCSEL, thus it is more suitable for the integration because there is no electrode at the bottom side. Since 650 nm and 850 nm lasers cannot penetrate through GaAs substrate, the original substrate must be removed and replaced with other transparent substrate such as gallium phosphide or thin silicon wafers for the light traveling to the bottom side. Then, we can fabricate a flat-tip microprobe array directly on the new substrate. After attaching a VCSEL array to the glass holder, the GaAs substrate of VCSEL was grinded mechanically to around 40  $\mu\text{m}$  thickness and followed by the chemical etching with  $\text{NH}_4\text{OH}/\text{H}_2\text{O}_2$  to remove the remaining substrate. It is possible to etch out just the remaining GaAs substrate by the chemical etching process since the VCSEL array includes an etch stop layer. After attaching a SOI wafer to this VCSEL array, we pressed them under constant stress and loaded them in the furnace at 250°C for 2 h for the direct bonding. The integrated VCSEL microprobe array can be realized by fabricating the microprobe array having small apertures on the SOI wafer using the techniques explained above. We believe this integrated nano-aperture VCSEL microprobe array is sufficiently effective to be fabricated and applied to the parallel recording head, though further research is still required to confirm the optical usefulness of this new VCSEL microprobe array. Currently we are attempting to evaluate the optical properties of flat-tip microprobe arrays and improve the head structure to complete the parallel near-field optical recording system using the integrated VCSEL microprobe array.



**Figure 7.** Schematic diagram of the layer structure of near-field phase change media and the integrated VCSEL microprobe array prepared using a bottom emitting VCSEL. (Contact pads of this array are not shown in this figure.)

### Simulation results for the reading mechanism using optical feedback in VCSEL

Both types of conventional optical media, the magneto-optical (MO) and phase change (PC) disks, are considered to be applied to our two-dimensional optical system. In case of the MO media, the system requires extra reading array head of giant magnetic resistance (GMR) element to get magnetic signals from the media. However, we can use the same recording array head to detect the reflective difference from the crystalline and amorphous phase for the PC media without any other reading head or optical elements. The basic concept of this reading mechanism was developed using a stripe laser diode before, including our research work for the lensless optical floppy disk [8,9]. The change of output power in the semiconductor laser is induced by the optical feedback from the external surface of different reflectivity using an external oscillation, which can be detected by measuring the voltage change between two electrodes of laser diode [9,10]. In this study, the VCSEL characteristic of voltage change in the integrated VCSEL microprobe system was analyzed theoretically as a function of the amount of returning light from the media that depends on the reflectivity of media. A FDTD simulation was applied to analyze the amount of returning light in this system, including the VCSEL, microprobe and phase change media, as explained in figure 8(a). In the calculation, we assume that the inside material and outside area consist of GaP and vacuum, respectively. The microprobe has a pyramidal shape with a 55 deg angle between the two side planes because it is supposed to be prepared from (100) GaP wafer by the chemical etching. The optical beam of an 850 nm wavelength VCSEL propagates from the base plane to the microprobe, where the oscillation modes of electric and magnetic fields are parallel to the  $x$  and  $y$  axis, respectively. The PC media consists of 20-nm-thick dielectric layer ( $\text{ZnS-SiO}_2$ ), 20-nm-thick  $\text{Ge}_2\text{Sb}_2\text{Te}_5$  layer, 20-nm-thick dielectric layer ( $\text{ZnS-SiO}_2$ ), and 100-nm-thick reflective Al layer. The observation plane for the reflectivity difference is assumed at the location  $0.1\mu\text{m}$  below the VCSEL emitting surface.

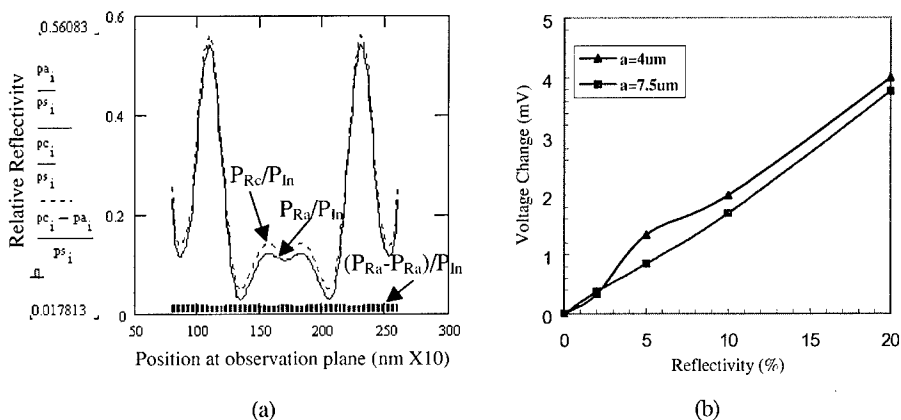


**Figure 8.** (a) Analysis model for an optical feedback effect in the integrated VCSEL microprobe array and (b) the electric field distribution for the crystalline phase of the PC media. The observation plane is assumed at the location  $0.1\mu\text{m}$  below the VCSEL emitting surface.

Figure 8(b) shows the electric field distribution of the integrated VCSEL microprobe for the crystalline phase of the PC media. As expected, the light is reflected both by the Au metal layer of the microprobe surface and the crystalline phase of the media. From the field distribution for the crystalline and amorphous phase, we can calculate the relative reflectivity of two different phases by dividing them to the initial VCSEL field separately. The difference of relative reflectivity is shown in figure 9(a) as a function of the location in the x direction at the observation plane. It shows roughly 3% reflectivity difference even though there is a little variation with the location. From this reflectivity difference, we can calculate the carrier density in VCSEL using the continuity equation [11] and finally get the theoretical value for the voltage change using the equation:

$$\Delta V = \frac{2kT}{q} \frac{\Delta N}{N_0}$$

where  $N$  is the intrinsic carrier density,  $k$  is Boltzmann's constant,  $q$  is the electron charge and  $T$  is the temperature. The voltage change across two electrodes in the VCSEL is summarized as a function of the reflectivity difference in figure 9(b). The voltage change due to the optical feedback increases linearly with the reflectivity difference and shows higher value for the VCSEL having smaller emitting surface. For the 3% difference in the integrated VCSEL microprobe, the voltage change results in around 0.8mV for the 8  $\mu\text{m}$  diameter emitting VCSEL. Though this value is a little low to be applied to the actual reading head, it still has a possibility to detect the signals from the phase change media. From the simulation results, we can conclude that the voltage change will increase with the shorter distance from the VCSEL to media (for example, smaller size of microprobe), smaller diameter of the VCSEL emitting surface and higher reflectivity difference in the phase change media through the improvement of disk structure.



**Figure 9.** (a) The difference of relative reflectivity as a function of the location in the x direction at the observation plane ( $P_{In}$ =initial electric field,  $P_{Rc}$  and  $P_{Ra}$ =reflected field from the crystalline and amorphous phase) and (b) the voltage change across two electrodes in VCSEL. The voltage change results in 0.8mV for the 8 $\mu\text{m}$  diameter emitting VCSEL with a 3% reflectivity difference.

## SUMMARY

To actualize more effective and simple data storage of a high data capacity and fast data transfer rate, two-dimensional near-field optical system has been studied using a vertical cavity surface emitting laser (VCSEL) microprobe array. We have developed some candidates for the parallel recording head, including the direct aperture formation on the VCSEL emitting surface and the preparation of microprobe arrays with the flat-tip structure. Apertures with a minimum size of around 50 nm have been prepared using a FIB method after depositing the phase matching layer of  $\text{Si}_3\text{N}_4$  and reflective layers of Cr and Au on the emitting surface. For the VCSEL having a 50-nm-thick metal layer, the optical output increases 7  $\mu\text{W}$  after the aperture formation of 100-nm-diameter. In order to increase the optical output through a tiny aperture, we also developed new flat-tip microprobe array that has advantages for improving the optical efficiency and stabilizing the contact head system with the optical media. Silicon and GaP nano-aperture microprobe arrays have been prepared successfully with the aperture size below 200 nm using micro-fabrication techniques. We have also studied the integrated VCSEL microprobe array by the direct fabrication of flat-tip microprobes on the substrate of bottom emitting VCSEL. The reading mechanism has been investigated theoretically using a FDTD simulation and an optical feedback effect from the phase change media for the integrated microprobe VCSEL array. The voltage change due to an external reflection can increase with the smaller emitting surface in VCSEL and shorter distance from the VCSEL to media, which leads a guideline for the signal detection in the external reflection mode. We believe this nano-aperture VCSEL microprobe array is sufficiently effective to be applied to the parallel recording head for the near-field optical data storage with a high data capacity and fast transfer rate.

## ACKNOWLEDGEMENTS

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